May 2013

Massachusetts Biomass Heating Conversion

Armir Bashllari
Worcester Polytechnic Institute

Stephan Janvier Montanez-Sanchez
Worcester Polytechnic Institute

Tyler Jarrett Menard
Worcester Polytechnic Institute

Massachusetts Biomass Heating Conversion

AN INTERACTIVE QUALIFYING PROJECT

SUBMITTED TO WORCESTER POLYTECHNIC INSTITUTE IN PARTIAL FULFILLMENT FOR THE DEGREE OF BACHELOR OF SCIENCE

Armir Bashllari

Tyler Menard

Stephán Montañez-Sánchez

Professor Robert W. Thompson, Project Advisor

Abstract

This project looked at the feasibility of converting Massachusetts' commercial heating sector into a wood pellet heated one. The availability of the wood pellets and wood pellet boilers were observed, as well as the availability of other fuel sources and the emissions released from said boiler systems. Anna Maria College, which recently converted to wood pellet heating, is used as an example in this project.

Table of Contents

Table of Figures

Table of Tables

1. Introduction

Wood pellets are a low-cost, sustainable carbon neutral source of energy that is readily available in the New England states. Wood pellets, much like other fuels, have emissions that have to be observed to determine any health or environmental issues that may arise because of them. While wood pellets are a product of wood, they contain lower levels of moisture in them, which is what makes them more efficient and cleaner burning than simple wooden logs.

Wood pellet emissions can't be disregarded however as they can be hazardous to both our health and the environment. They must be observed in the same way as other differently fueled boilers, by following the National Ambient Air Quality Standards. These standards can also serve as an initiative to choose which boiler to use in a determined area, seeing as how a high particulate matter (PM) location might not be ideal to put a wood pellet boiler as PM are one of the main emissions from said boilers.

The goal for this project is to use this information to determine the feasibility of switching commercial heating in Massachusetts to wood pellet heating. Wood pellet and other fuels supply availability, costs, and the amount of wood pellet boilers that can be available need to be taken into account in order to achieve our goal. Since they recently (summer 2012) changed to wood pellet heating from #2 oil, we used Anna Maria College in Paxton, MA as an example for this project.

2. New England Forests History

New England has a variety of forests within its territory. These forests differ from size, density and the type of trees within each. They also have different laws regarding forestry. New England is composed of several States: Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. We can also include New York and several Canadian provinces like Quebec and New Brunswick because of their proximity to the area.

The forests of New England are divided as so: Maine has 17.7 million acres of forests, it covers about 90% of the state, Massachusetts contains 3.2 million acres of forest covering 63% of the state's land area, Rhode Island has 393 thousand acres which is about half of the state's area, New Hampshire has about 4.8 million acres of forest (around 80% of the state area) and is on the decline, Vermont has 4.6 million acres of forests (75% of the state area), Connecticut is about 2.2 million acres of forest (62% of the state area), New York has 18.95 million acres (55% of the state), New Brunswick has about 14.5 million acres (80% of the province) and Quebec has over 188 million acres of dense forest zone (around half the province) (Rigorous and Adaptive Forest Management - Main highlights,).

The forests are divided into 4 categories: alpine communities, coniferous, northern hardwood and wetlands. Alpine communities are essentially arctic regions and are treeless, since they are restricted to the mountain tops that reach an elevation higher than the tree line, which is about 1300 meters. Coniferous forests are found in the White Mountain regions and the northern parts of New England Uplands, primarily the middle interior of Maine, especially in the area between 900 and 1300 meters of elevation. Northern hardwood forests also go by the name hemlock-northern hardwoods, and mixed forests; they're located in the seaboard lowlands and south of coniferous forests. Wetlands are divided into 3 categories: bogs, swamps and bottomlands; bogs have almost no trees if at all and swamps and bottomlands have more diversity of trees.

2.1 Massachusetts Forests History

Massachusetts is heavily forested, despite the fact that 841 people per square mile make it the third most densely populated state in the nation (U.S. Census 2010). The state contains 3.2 million acres of forest covering 63% of the land area (An Assessment of the Forest Resources of Massachusetts, 2010). 85% of those forested acres are classified as timberland (i.e., capable of growing more than 20 cubic feet per acre per year, and not withdrawn from harvesting) according to the USDA Forest Service. Current forest management is highly varied due to the diverse ownership pattern (Alerich, 2000).

The structure and composition of Massachusetts' forests are a legacy of historical patterns of natural and human disturbance. In the mid-nineteenth century, nearly 70% of the land was cleared for agriculture, and the remaining forests were cut, burned and grazed. In the late 1800's, agriculture declined and second-growth forests, dominated by white pine, established across the region's abandoned farmland. This supply of white pine spurred a timber harvest bloom that peaked in 1910-1911 and yielded even-aged stands of predominantly hardwoods. White pine is especially susceptible to windthrow and the 1938 hurricane continued the process of forest conversion from pine to even-aged hardwoods. Today, the most common tree species are red maple, eastern hemlock, and white pine (Alerich, 2000).

Since 1938, logging and forest succession have been the main forces shaping forest composition. However, harvesting has not kept pace with tree growth since at least 1957, and over the past decades, wood volumes have increased for both softwoods and hardwoods. The history of lumber production corroborates the high productivity of the Massachusetts forest. In spite of the fact that very little of the landscape was in the mature forest in 1869, lumber production was twice then what it is today. Given the aggressive way that the forests rebounds from disturbance and regenerates naturally, it is logical to look at the extent to which this resource can meet some of the consumptive need for wood (The Illusion of Preservation, 2002).

2.1.1 Wood Consumption-Production Ratio

Limited and often poor forest management, coupled with a prosperous standard of living suggests that Massachusetts has embraced the "illusion of preservation". International comparisons highlight the consumption-production disparity. Massachusetts is comparable to Germany, Switzerland, Japan, and France in forest cover and the ratio of human population to forest area. Yet, assuming that U.S. averages apply to Massachusetts, per capita consumption is 3 to 4 times the level in these countries. However, Japan harvests nearly 5 times the wood volume per hectare of forest than Massachusetts, and Germany's harvest rate is 17 times greater. As in most of the U.S., there is little connection between lifestyle and resource production in Massachusetts (The Illusion of Preservation, 2002).

2.1.2 Lumber Market

Massachusetts currently generates a small amount of structural lumber, primarily from white pine, which is light, strong and easily worked. The other major softwood species is hemlock, which is used less frequently, but like white pie, is used for framing and home construction. These 2 species could substitute in many applications for Douglas fir and Sitka spruce from the Pacific Northwest and British Columbia. More than half the lumber sawn in Massachusetts is oak, which is highly valued for furniture and other uses. However, red maple, the most common tree species, is rarely utilized, despite its potential as a substitute for imported wood in the construction of flooring, furniture, and polymer-plastic products. The pace of wood product substitution is accelerating, especially outside of the U.S., and there may be an opportunity to increase the utilization of this hardwood species (The Illusion of Preservation, 2002).

2.1.3 Shifting the Consumption-Production Ratio

Data on wood production and consumption in Massachusetts are rough, but annual harvest figures from the Department of Environmental Management's (DEM) Forest Cutting Plan applications support the widely held conviction that total harvest volumes are low and only equivalent to about 2% of wood consumption gauged by national rates. The amount of wood produced annually from Massachusetts forests is further complicated by the fact that some wood is produced by the one-time conversion of forests to other developed uses. Even the extent of land conversion varies, with Massachusetts Audubon estimating 16,000 acres of “open space” lost annually between 1972 and 1996, and the USDA Forest Service estimating a loss of 281,000 acres of timberland between 1985 and 1998. Forest Service FIA (Forest Inventory Analysis) results indicate an average of 6,282 board feet per acre of timberland. This represents an estimated total one-time removal of 126,000,000 board feet annually through land conversion. Annual harvest removals from forest land that remains forest are estimated to be 311,190 m^3. Thus, even if all volume removed through land clearing were captured commercially and converted to usable product, while it would almost double the amount of product, it would still represent a small increase in the total amount produced compared to what is consumed. Also, it is important to remember that this is a one-time, completely non-sustainable contribution towards meeting consumption (The Illusion of Preservation, 2002).

Estimates of wood consumption in Massachusetts are based on overall American per capita consumption rates, and the current Massachusetts population. Consumption is estimated to be the simple difference between the amount of wood that the United States produces, imports, and exports. Consequently, these estimates of consumption do not include a sensitivity to the amount of recycled material that may be used and substituted for original wood. Consumption in this case simply refers to the amount of wood product used, and does not incorporate estimates of recycling (The Illusion of Preservation, 2002).

3. Wood Pellets

3.1 What are Wood Pellets?

Wood pellets are short cylindrical pieces that are made from compressed biomass; this biomass is typically sawdust, wood chips, wood shavings and/or other wood waste materials like scraps. Typically the diameter of pellets is 8 mm in Nordic Countries, 6mm in Central Europe (Additives in Wood Pellet Production, 2011), and sometimes 15 mm up to 25 mm according to CEN/TS 14961. It takes about 1.92 tonnes of raw material to make 1 tonne of pellets and about 2.2 tonnes if using materials to heat the furnace; this reduction in mass is due to the evaporation of moisture in the wood, which is what also makes the pellets more efficient when being burned (Pellet System International). Wood pellets are a good source of energy, being less than 8% moisture and having an ash content of less than 1%; they are a highly efficient and clean source of fuel, providing around 8000+ BTU/lb of wood pellets. Best of all they are cheap (around $250/ton), with a relatively low cost variation in comparison with other fuel costs, such as fuels made from processed petroleum.

However, it has been noticed that pellets may decompose during storage, which forms gases such as carbon monoxide and hexanal that are hazardous to human health; this typically happens with pellets made from softwoods. And ventilation of storage rooms, where this problem is most notable, containing wood pellets in accordance to regulations still may not lower CO concentrations to a non-life-threatening level (Additives in Wood Pellet Production, 2011).

3.1.1 What are They Made of?

Wood pellets are typically made from sawdust collected from logging residues. There aren’t many companies logging wood just to create sawdust, most of them buy the residue from other similar activities, but with a higher demand of wood pellets each year, companies may start to meet the demand. The other materials that can be used to make wood pellets, these pellets have different values than the ones previously mentioned, are: hay, straw, spoiled grain, canola sludge, switch grass, willow and even peat moss. They don’t add any additives for binding when using wood as the material for the pellets, the reason being the lignin in the wood acts as a natural binder.

3.1.2 How are They Made?

Wood pellets are made through a process requiring various steps. First, typical wood pellets start as a variety of differently sized wood objects, from sawdust to larger wooden objects. This initial material goes through hammer mills and/or mills to get ground up to the necessary homogenous size of about 5 mm; moisture is also removed in the process, this is critical because the lower the moisture content . Then, the resulting ground material is fed to a press and pressed through a die with holes of the required size. The press' high pressure and friction causes the temperature of the wood to rise, slightly plasticizing the lignin contained in the wood within the temperature range of 100 and 130 °C (Additives in Wood Pellet Production, 2011). They then need to be cooled; the lignin still being warm from the pellet producing process makes them stick together.

3.2 Why Wood Pellets Instead of Logs?

Although they come from the same source, wood pellets and logs burn quite differently. Logs used for firewood typically have a moisture content of around 50%, with well seasoned wood having a lower moisture content of as little as 25%. This high moisture content, along with the fact that logs generally have some bark on them, which has a very high ash content, contributes to wood pellets being a much cleaner fuel source than unprocessed wood logs.

3.3 Harvesting Wood for Pellets

3.3.1 Regional Restrictions

While there are no general restrictions to burning wood pellets in the United States, some countries or areas within them have laws and/or regulations for carbon emissions, areas included in these are transportation and energy production. Wood pellets come out as a great advantage because they are carbon neutral (processing a carbon amount equal to that which is going to be released when burning the pellets.) when taking into account the years the tree spent processing the air before being cut down.

3.3.2 Currently Available for Harvest

There is a vast supply of wood in the New England area, although not all of it is harvestable due to the resource being localized in areas that the necessary machinery cannot be placed; this is the result of location, the supply may be at cliffs or near wetlands. Currently, logging in New England is mostly practiced in: Maine, Vermont and New Hampshire.

The majority of the forests of New England (85% in 1990) are classified as one of the major forest-type groups: white pine, spruce-fir, oak-hickory or northern hardwoods. Across New England, 82 tree species or species groups were recorded on forest survey plots (USDA Forest Service, Forest Health Monitoring in New England: 1990 Annual Report).

3.3.3 Types of Wood Used

3.3.3.1 Hardwood vs. Softwood

The types of wood used in making the pellets are not as important as the moisture control done on them during the production process. In their natural form hardwoods have a lower moisture content and therefore burn longer, and softwoods have more sap or pitch making them easier to light, but burn more quickly. The pelletizing process takes away many of these differences. The reason being that the sawdust came from softwood, hardwood or a blend; they are still compressed to the same density. The BTU's of various species of wood are very similar on a per unit mass basis; wood pellets being about 8000 BTU/lb at 6% moisture (Hardwood vs. Softwood).

3.3.3.2 Grades of Wood

The grade of a particular piece of lumber may be determined when the tree is harvested, known as a field grade, and is determined by the diameter at breast height (DBH) of the section to be harvested, the scaling diameter (the diameter at narrow end of the cut), and the number of defects present on the surface of the wood. To find the field grade, the harvested wood is divided into four long, equal-width sections running down the length of the log with one of these sections containing the greatest possible number of defects. Defects include knots, branches with a diameter of >3/8", stress fractures, decay, and bends such as crook and sweep. This worst face is then ignored for grading purposes. After this worst face is eliminated, the next best is used as the tree grade, so long as the log meets the other criteria for this particular grade.

Grading Factors		Log Grades				
		Tree Grade 1			Tree Grade 2	Tree Grade 3
Length of grading zone, *feet*		Butt 16			Butt 16	Butt 16
DBH minimum, *inches*		16+			13+	10+
Scaling diameter, *inches*		13	16	20+	12+	8+
Clear cuttings	Minimum length, *feet*	7	5	3	3	2
	Maximum number	2	2	2	3	No-limit
Minimum cumulative length of clear cuttings (12-foot section), *feet*		10	10	10	8	6
Minimum cumulative length of clear cuttings (14-foot section), *feet*		11.7	11.7	11.7	9.3	7
Minimum cumulative length of clear cuttings (16-foot section), *feet*		13.3	13.3	13.3	10.7	8
Maximum sweep and crook allowance		15%			30%	50%

Adapted from USDA Forest Service standard grades for factory lumber logs from Rast et al. (1973).

Table 1: Lumber Grading

4. Emissions

4.1 Introduction to Biomass Heating and Energy

The installation of a wood pellet biomass boiler or furnace is essentially the same as any other boiler or furnace installation. The systems, at least those used in a commercial setting, tend to incorporate some sort of storage silo for the fuel, as the fuel needed for a large commercial building can total several hundred tons over the course of a heating season. For residential installations, a smaller silo may be used if the customer chooses to receive bulk shipments of loose pellets, or the pellets may be shipped and stored in individual 40 pound bags.

A typical biomass heating system consists of only a few parts and is very similar to most other types of boilers. Firstly, there is the hopper, a container which a small amount of fuel (generally a couple of day's or week's worth depending on the system) of pellets are loaded in to be fed into the furnace. Most hoppers in home heating pellet stoves must be manually loaded when needed by adding pellets from the silo or bags used for storage, so minimizing the amount of effort needed to move pellets from storage to hopper is key to keeping the system maintained efficiently. For larger industrial systems, it may be beneficial for the silo to be connected to the hopper via an auger, allowing for the hopper to be refilled at the push of a button. Of course attaching the silo to the hopper requires that the two be relatively close together and easy to connect. However it is fed, the hopper is connected by an auger to the combustion chamber where the pellets are initially ignited and where the new pellets are fed. From here, the ash falls into an ashtray, which may be cleaned either manually by simply emptying it out when it gets full (a simple task for a residential system, but one which can become much more daunting when the system burns hundreds of tons of fuel a year) or by having an automated blower installed to clean out the ashtray, although this itself will need maintenance regularly to remove any potential buildup. The heat generated is captured by some means, usually by heating water and circulating it through the area to be heated, and regulated so that an appropriate amount of fuel is burned and heat is kept at the desired level. Residential wood pellet fireplaces operate in a similar manner, but instead of having a boiler element, there is a series of pipes connected to a blower. The heat from the combustion chamber is used to heat the pipes and the blower forces air through the pipes to heat the room.

Another method of burning biomass, gasification, involves reacting biomass fuels at high temperatures to produce hydrogen gas and combustion byproducts. Gasification has been used as an alternative to fossil fuels since World War II. By 1945, in Europe there were as many as 9 million trucks, buses, and agricultural achiness powered by gasification. While this method of converting biomass into energy does not provide any reduced amount of CO_2 or CO when compared to a normal biomass burning heat or energy system, the gases that are released can be captured and further refined to be cleaner burning, without releasing harmful byproducts into the atmosphere, only the water vapor produced from hydrogen combustion. The ash left behind, which contains the same heavy metals and minerals as the ash and smoke produced by normal biomass incineration, can also be processed by heating it to very high temperatures, producing a chemically stable slag of glass-like material. Generating power from gasified biomass is a rather efficient process in itself.

4.2 Carbon Neutrality

A highly advertised aspect of wood pellet heating is that it burns cleaner than fossil fuels. According to a study conducted by David Dixon of Dirigo Environmental Consultants, pellet stoves actually release 50 times as many particles into the air as oil furnaces. This particulate matter can cause respiratory complications in people and even impair visibility at higher concentrations. However, UNH natural resources professor John Aber has stated on the matter that "carbon dioxide emissions are key," and burning wood pellets is carbon-neutral if done renewably (forster.com, 2008). This means that burning biomass such as wood pellets in this manner does not contribute to the greenhouse effect. Yet, the full potential of cleaner burning fuel from wood pellets can only be realized with policies that enforce proper procedures for manufacturing and burning wood pellets. For example, wood pellet production facilities dry the sawdust and wood matter before they are compressed into pellets. The lower the moisture content, the cleaner the fuel will burn. Policies would not only require treatment of emissions from burning pellet fuels to reduce particulates, but also treatment of gases emitted from drying wood matter during pellet production.

Many countries in Europe that use coal plants for energy are slowly making a change to wood pellets, although it is less expensive to burn coal. This is due to the European carbon tax, which requires coal plants to meet certain carbon emission standards or pay a fine. The fine makes it cheaper to burn wood pellets because it is considered carbon-neutral as long as the wood pellet supply is imported from a sustainable source. Another method that is used in coal plants is retrofitting the facility to also burn biomass. This way both coal and wood pellets can be burned, allowing for a cost-effective way to reduce carbon emissions (renewableenergyworld.com, 2012).

4.3 General Boiler Emissions

There are generally six pollutants that are monitored when it comes to Boiler emissions. These pollutants are ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, lead, and particulate matter. As of 1990, the Clean Air Act requires the EPA to maintain the National Ambient Air Quality Standards (NAAQS) for these six pollutants. Many areas in the United States violate some of these standards, most notably, much of California and some areas in New England. Techniques for controlling these emissions have been developed over the years to help remedy this over-pollution.

National Ambient Air Quality Standards (As of August 2011)				
	Primary Standards		Secondary Standards	
Pollutant	Level	Averaging Time	Level	Averaging Time
Carbon monoxide	9 ppm ($10\ mg/m^3$)	8-hour [1]	None	
	35 ppm ($40\ mg/m^3$)	1-hour [1]		
Lead	$0.15\ \mu g/m^3$ [2]	Rolling 3-Month Average	Same as Primary	
Nitrogen dioxide	53 ppb [3]	Annual (Arithmetic Average)	Same as Primary	
	100 ppb	1-hour [4]	None	
Particulate Matter (PM_{10})	$150\ \mu g/m^3$	24-hour [5]	Same as Primary	
Particulate Matter ($PM_{2.5}$)	$15.0\ \mu g/m^3$	Annual [6] (Arithmetic Average)	Same as Primary	
	$35\ \mu g/m^3$	24-hour [7]	Same as Primary	
Ozone	0.075 ppm (2008 std)	8-hour [8]	Same as Primary	
	0.08 ppm (1997 std)	8-hour [9]	Same as Primary	
	0.12 ppm	1-hour [10]	Same as Primary	
Sulfur dioxide	0.03 ppm [11] (1971 std)	Annual (Arithmetic Average)	0.5 ppm	3-hour [1]
	0.14 ppm [11] (1971 std)	24-hour [1]		
	75 ppb [12]	1-hour	None	

Table 2: National Ambient Air Quality Standards

4.3.1 Nitrogen Oxides

The nitrogen compounds that are emitted are nitric oxide (NO) and nitrogen dioxide (NO_2). Most of what is directly emitted is NO that reacts to form NO_2 in the atmosphere. It is NO_2 that then reacts with other pollutants to produce ozone (O_3), which is what makes up most of smog. The pollutants that react with NO_2 stem from the vaporization of fuels caused by poor combustion or leaks in pipes. Various methods exist for reducing the emissions during and after the combustion process. One such method is firing low excess air to limit the amount of excess nitrogen and oxygen that goes into the fire. However, lowering this by too much can cause incomplete combustion, resulting in increased carbon monoxide (CO) emissions. Carbon monoxide can be fatal at high concentrations, so it is crucial to keep CO levels low. For oils, the most effective means of reducing nitrogen oxide emissions is to have the oil itself contain lower levels of nitrogen. This can allow for reductions of as high as 70% in nitrogen oxide emissions compared to Number 2 oils.

Other methods of reducing Nitrogen oxide emissions are called post-combustion control methods, which look at reducing NO and NO_2 levels in the flue gas and are usually much more expensive than combustion control methods. One of these is Selective non-catalytic reduction, where ammonia is injected into the flue gas at temperatures of 1,400 to 1,600 degrees Fahrenheit to react with the nitrogen compounds and produce clean nitrogen gas and water vapor. This can reduce nitrogen oxide emissions by up to 50% but may be troublesome to implement in large industrial boilers where the location of flue gas at the specific temperature is constantly changing. Instead another method is to use a catalyst to allow for the reaction to take place at a lower temperature. The issue with this is that it is rarely cost-efficient for commercial-sized boilers that output less than 100 MMBtu/hr, but the reduction in nitrogen oxides can be as high as 90%. (cleaverbrooks.com)

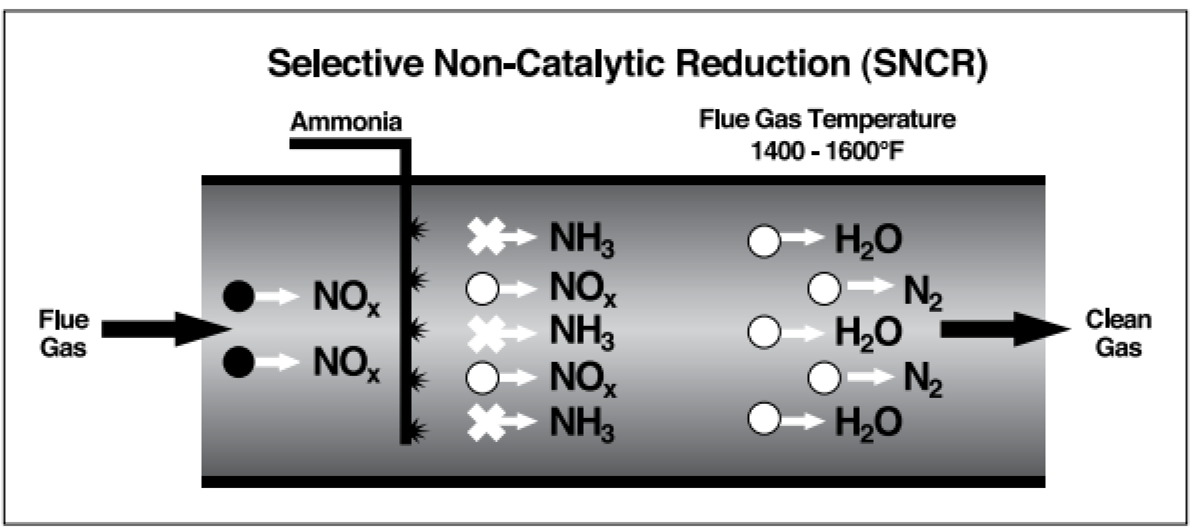

Figure 1: Selective Non-Catalytic Reduction

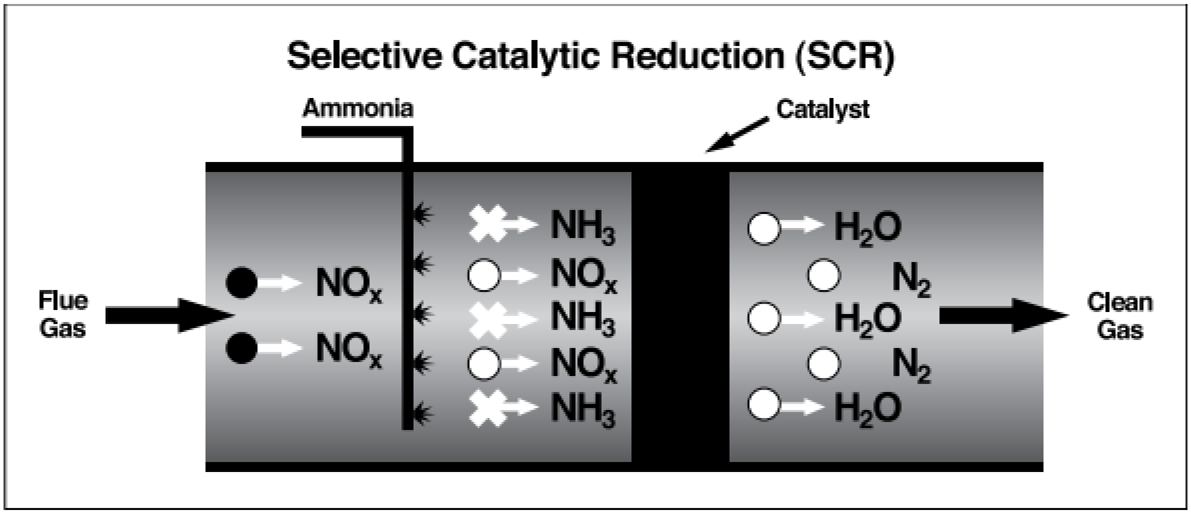

Figure 2: Selective Catalytic Reduction

4.3.2 Sulfur Oxides

Most of the sulfur emissions from a boiler will consist of sulfur dioxide (SO_2), the rest will be either sulfur trioxide (SO_3) or sulfate particulates. Sulfur compounds are known to form sulfuric acid (H_2SO_4) when introduced to water vapor, which is not only found in the atmosphere, but also in the flue gas emitted. This causes the toxic compound to be found in things such as fog, snow, and rain (acid rain) and is severely harmful to the environment.

The magnitude of sulfur emissions is directly related to the sulfur content in the fuel, so it is only a real concern with oil fuels and coal. In the past, the solution was to have a tall stack so that the sulfur emissions would stay away from the ground level. But with the rise of boiler emissions in the world comes the need to actually reduce sulfur oxide emissions. Just like the case with nitrogen, the most effective way to reduce sulfur content is to use fuels with low sulfur content. Another, much more expensive method, is to use flue gas desulfurization (FGD), where the sulfur oxides are removed from the flue gas by scrubbers. FGD can be non-regenerable or regenerable. In non-regenerable FGD, waste product is produced that needs to be disposed of, whereas in regenerable FGD, the waste is created into sulfur or sulfuric acid that can be sold. (cleaverbrooks.com)

4.3.3 Particulate Matter

There are two types of particulate matter: condensable and filterable. Condensable, or secondary, particulate matter is gaseous matter that condenses after discharge, whereas filterable, or primary, particulate matter consists of the particulate matter that is directly emitted. Both of these need to be regulated in order to maintain clean air quality. There are various types of compounds that make up particulate emissions, such as nitrates, sulfates, carbons, and oxides. These pollutants are harmful not only to the environment, but to people as well.

There are also two categories of particulate matter pertaining to their sizes: PM 2.5 and PM 10. PM 2.5 refers to particles that are 2.5 micrometers in diameter or smaller, whereas PM 10 refers to particles that are greater than 2.5 micrometers up to around 10 micrometers in diameter. Of the two, PM 2.5 is more hazardous simply because of its small size. To put it into perspective, a strand of hair is about 70 micrometers wide. PM 10 is 7 times smaller than a strand of hair and PM 2.5 can be 40 times smaller than a strand of hair. PM 10 is large enough for most of it to be naturally filtered out by our bodies before getting to the lungs. On the other hand, PM 2.5 is small enough to get deep into the lungs and into the alveoli where it can affect gas exchange. It can even enter the bloodstream through the lungs. Because of this, long term exposure to small particulate matter not only damages the lungs, but can cause cardiovascular disease. Studies have shown that there is “an 18% increase in deaths from heart disease among people with long term exposure to particulate matter.” (hcdoes.org) Our bodies have no effective mechanism for dealing with particles this small, which is why the Environmental Protection Agency (EPA) has put regulations on the amount of particulate matter that is allowed in the air for the United States. Currently, the standard for PM 10 is 150 mcg/m^3 for any given 24-hour period. The standard for PM 2.5 15 mcg/m^3 for an annual average and 35 mcg/m^3 for any given 24-hour period. The hazardous effects of PM 2.5 have only been looked into fairly recently. It was essentially lumped in with PM 10 until around 1997, where the standard for PM 2.5 was 65 mcg/m^3 for any given 24-hour period. Particulate matter emissions are of great concern for burning biomass fuels since they release more particulates than any other fuel sources. Unlike carbon emissions however, particulate emissions can be reduced through filtering. Reducing particulate matter emissions is key if wood pellets are to be a viable source of energy while still maintaining a healthy environment.

4.4 Reducing PM emissions

The current particulate emissions standard for boilers is 0.10lb/MMBtu. As well as this, a Continuous Emission Monitoring System (CEMS) must check that a boiler's emissions do not exceed 20% opacity (gpo.gov). There are no regulations for natural gas boilers since their emissions of particulates is very low. When it comes to firing oils and wood, most of the particulates are made up of various hydrocarbons, the rest comes from sulfur and nitrogen compounds or other uncombusted elements.

There are several ways to go about reducing particulate matter emissions. The most effective and cost efficient way to do this, especially when it comes to oils, is to use cleaner fuel. This means having low nitrogen or sulfur content, or limiting the amounts of other particulate causing constituents. Other methods include the use of electrostatic precipitators, scrubbers, and baghouses. For electrostatic precipitators, the smoke is first run through a negatively charged electrical terminal, giving the smoke a heavy negative charge. Afterwards, positively charged plates attract and collect the particles over time. The plates need to be cleaned regularly as the particles accumulate (explainthatstuff.com). When using scrubbers, the flue gas is filtered by running it through another substance. For particulate reduction, that substance is usually a liquid such as water. A solution that targets a specific compound can also be used. In baghouses, the flue gas is filtered through cloth fibers. The term baghouse comes from the fact that the smoke runs through an area containing multiple bags as seen in figure (...). Particles will accumulate on these cloth fibers and act as filters themselves. Although baghouses greatly reduce particulate emissions, they require a lot of space to utilize and the bags need to be replaced. Other complications may also come up, such as clogging or even fires. For pellet systems, using cleaner pellets is an effective way of reducing particulate emissions. This would mean using pellets with lower moisture and ash content. The use of pellets themselves is a cleaner form of woodburning compared to the use of wood logs. If using cleaner fuel is not possible or is not good enough of a solution, one of three methods above would have to be used. In fact, some method of reducing particulates is mandated by the EPA if the limit of 0.10lb/MMBtu is not met.

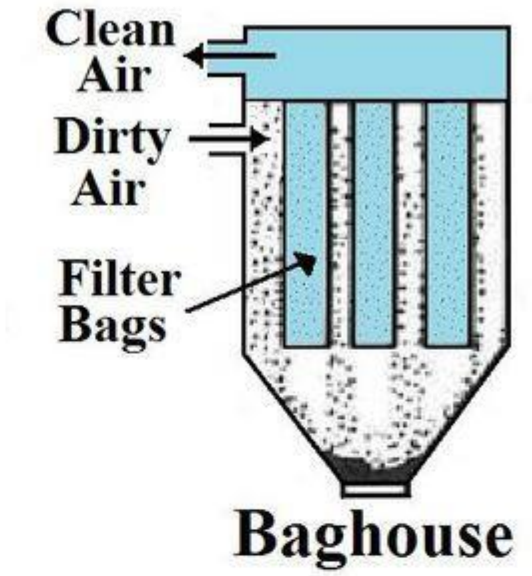

Figure 3: Baghouse

4.5 Issues on Pellet Storage

Dangerous gases are not only emitted during the burning phase of wood pellets. During storage, wood pellets can release a large amount of carbon monoxide and needs to be well ventilated so that the concentration does not reach toxic levels. In 2012, two deaths in Europe were reported to have been caused by carbon monoxide poisoning due to the storage of wood pellets. The carbon monoxide had been building up in the storerooms of these private households and even with the proper ventilation as required by regulations, the large concentration of carbon monoxide was not reduced. These two cases suggest that current regulations on pellet storage are insufficient for the safety of those working in them. There are several other cases of similar situations occurring during the transportation of wood pellets, even with small amounts of pellets of less than 6.5 kg. It has been found through studies of these cases that higher temperature can greatly increase the rate at which carbon monoxide is produced. Other factors include available oxygen, type of wood, moisture content, and the "freshness" of the pellets. Newer pellets tend to release more carbon monoxide through this reaction. (annhyg.oxfordjournals.org, 2012) What this translates to for others looking to use pellet heating is that the storage of pellets can be fatal if done improperly. All the cases mentioned dealt with the storage of pellets over long periods of time, so the buildup of carbon monoxide reached well over toxic levels. For places like Anna Maria College in Massachusetts, the silo holding the pellets is kept outside, with a tube that goes from the silo into the building where pellets are fed to the boiler. The supply of pellets is also renewed weekly, also alleviating the problem of carbon monoxide poisoning.

4.6 Summarizing Emission Properties of Different Fuel Types

The main sources for commercial heating come from natural gas, oils, coal, and biomass fuels. Natural gas produces the lowest amount of carbon emissions, yet burning biomass is considered carbon neutral if the fuel comes from a renewable source. Disregarding carbon neutrality, biomass such as wood logs can produce up to four times the carbon emissions as natural gas, so if the source of the wood logs is not renewable for any reason, the cleanliness of the air takes a large toll (pfpi.net). Wood pellets are a cleaner source of biomass fuel and reduce these emissions greatly. They are still not lower than that of natural gas, but due to carbon neutrality, carbon emissions can be considered zero. This is why wood pellets have been introduced as a clean fuel source.

The downside to pellets comes from their particulate emissions, which are much greater than that of oils and natural gas. Pellet boilers may need have certain particulate filters installed to deal with this, which is not only an additional cost but may also require additional maintenance. The particulate emissions for natural gas are so low that they are not regulated and in some cases not even recorded.

What it boils down to is that coals are the worst for the environment. They emit the most carbon and particulates (second only to biomass fuels other than pellets) but are cheap and abundant. Oils are better in terms of emissions, but they are scarce and more expensive. Natural gas is even better in terms of emissions and also cheaper than oil, however, it is also a non-renewable resource. Wood pellets are an alternate fuel source that are somewhere between coal and oils in terms of emissions, but are a renewable source and are considered carbon neutral if the fuel comes from a sustainable source. Of the first three fuels, natural gas is clearly the best in terms of cost and emissions. Throw in wood pellets to the mix and the question now becomes: which fuel type is best for a given situation?

4.7 Factors to Consider When Choosing the Right Fuel

4.7.1 Costs

Typically, one would want to pay as little money as possible for their heating. Different fuels not only come with different prices, but also require different infrastructure or additional features that add to the total cost of the entire boiler package. For example, if a boiler does not meet particulate matter emissions standards, a baghouse may be required to be installed for the boiler. This additional cost may be required for a pellet boiler system, but will not be necessary for any natural gas systems.

4.7.2 Emissions

Various areas of the United States break different parts the National Ambient Air Quality Standards. So if an area breaks the emissions standard for carbon dioxide emissions, they may be more inclined to choose a pellet heating system for the renewable supply of pellets. If the issue in the area is something like smog due to particulate emissions, natural gas would be the most environmentally friendly choice.

4.7.3 Location of the Boiler and Stack

The location of the boiler and stack is important because of the varying emissions properties of the fuels. A pellet boiler releases large amounts of particulates and the concentration of these particulates is much denser closer to the source of where it is emitted. If the stack is constantly surrounded by people, such as in a city, then a pellet system may not be ideal. Having people exposed to high concentrations of particulate matter can be very harmful to their health and cause fatal lung or heart problems in the long run. In fact, there are many other reasons that pellet systems are not practical in denser urban areas. Storage is a large issue for wood pellets. As mentioned before, improper storage of pellets can lead to toxic levels of carbon monoxide. Two solutions for this are to minimize the amount of time that pellets are stored by resupplying on something like a weekly basis or to maintain proper air flow where the pellets are stored. Both of these methods are more practical in remote areas, where the pellets can be kept in a silo away from people.

4.7.4 Heating Needs

Pellet boilers need to work at some minimum capacity in order to operate, which is not ideal if less heat than the minimum is actually required. There are solutions to this however, such as keeping a secondary oil or natural gas boiler for lesser heating needs.

5. Shifting Feasibility

5.1 Commercial Infrastructure of Biomass Heat and Energy

One of the main hindrances in converting from our current heating and electrical infrastructure to one fueled by biomass fuels is simply generating the required amount of fuel. Currently in Massachusetts, for commercial buildings totaling 10,000 sq. ft. or larger, the annual consumption of natural gas and fuel oil totals 142.3 trillion BTU (*Buildings Energy Data Book*). Using an estimate of wood biomass energy density (~8000 BTU/lb.) and some math we find that the required amount of wood biomass needed to supply New England's total fuel consumption would be approximately 8.9 million tons of dried and prepared wood biomass.

With current figures of wood harvest in Massachusetts totaling around 5.3 million tons usable for biomass fuel production; with 2.7 million tons coming from low grade harvested wood not usable for timber, 2.5 million tons coming from non-forest wood such as tree-care and landscaping, and around 100,000 tons coming from logging residue such as tree tops and limbs; there would need to be a large imported supply of wood biomass from either the bordering states, or Canada. Here, harvested biomass usable as fuel is considered to be rough cull trees, pulpwood trees, and low grade (grade 4 and 5) trees. These grades of harvest wood have little practical use as is, other than as fuel, due to their large amount of imperfections. Because of this, converting these harvests to biomass fuel would have little impact on other wood industries.

With a total forest area of approximately 246.343 million acres in New England, New Brunswick, and Quebec, assuming roughly the same harvest yields as forest in Massachusetts, we get a rough estimate of about 225 million tons of wood biomass usable for the production of fuel, capable of producing around 117.4 million tons of pellets. So clearly there is enough of a supply of wood biomass for all heating in Massachusetts should all currently available resources be called upon.

While the supply of unprocessed wood may be available the production capabilities of nearby biomass sources are still lacking. The entire world production of biomass, as reported by the consulting firm Pöyry, in 2010 totaled 13.5 million tons, with only around 4.9 million tons being produced in North America. However, the amount of biomass fuel produced in North America has been increasing steadily from just over a million tons in 2003, with several pellet production facilities currently being constructed in the southern United States.

Boiler manufacturers also control the future expansion of the biomass heating market and must be capable of meeting the demands of a growing industry. At the current time, the majority of the boiler manufacturers are located in Canada and Europe, with very few boiler manufacturers in the United States and none in New England. Because of this, boilers must be imported or shipped in from other parts of the country or world. For example, the boilers installed by Biomass Commodities are typically produced by Solagen Inc., a company based in Oregon. However, while there may not currently be much market presence in New England for boiler manufacturers, the industry is set to expand and is only waiting for the demand to increase before investing a substantial amount.

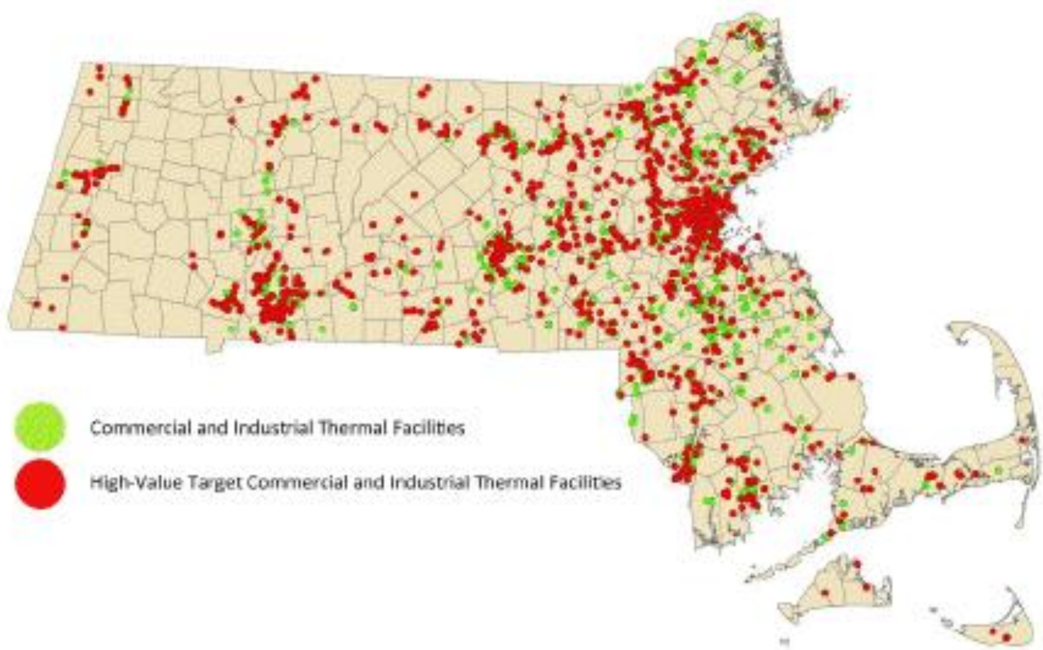

Figure 4: Commercial and Industrial Thermal Facilities in Massachusetts

So, while there may be an abundant supply of fuel and enough of interest in the industry for local manufacturing facilities to be built in New England, should the demand arise, there is one factor that does limit the adoption of wood pellet fueled biomass furnaces: natural gas. Many commercial buildings, which are prime targets for conversion as they will experience the greatest amount of savings, are located in urbanized areas which have natural gas pipelines installed to supply them with a fuel that is not only cleaner burning than wood pellets, but currently less expensive as well with natural gas costing around $4.15/MM BTU and wood pellets costing around $12-$16 depending on several factors, including quality of the pellet, energy density of the wood, completeness of burning of the pellet. At 3-4 times the cost of natural gas, and with natural gas prices decreasing year to year, wood pellets, at least for the near future, may not be a very attractive option for many companies. As seen in the figures below, areas such as Boston, Worcester, and Springfield, which contain the majority of the commercial and industrial buildings, are places where the majority of homes are not heated with oil or electricity, indicating that there is already some sort of alternative to these options available, which happens to be natural gas.

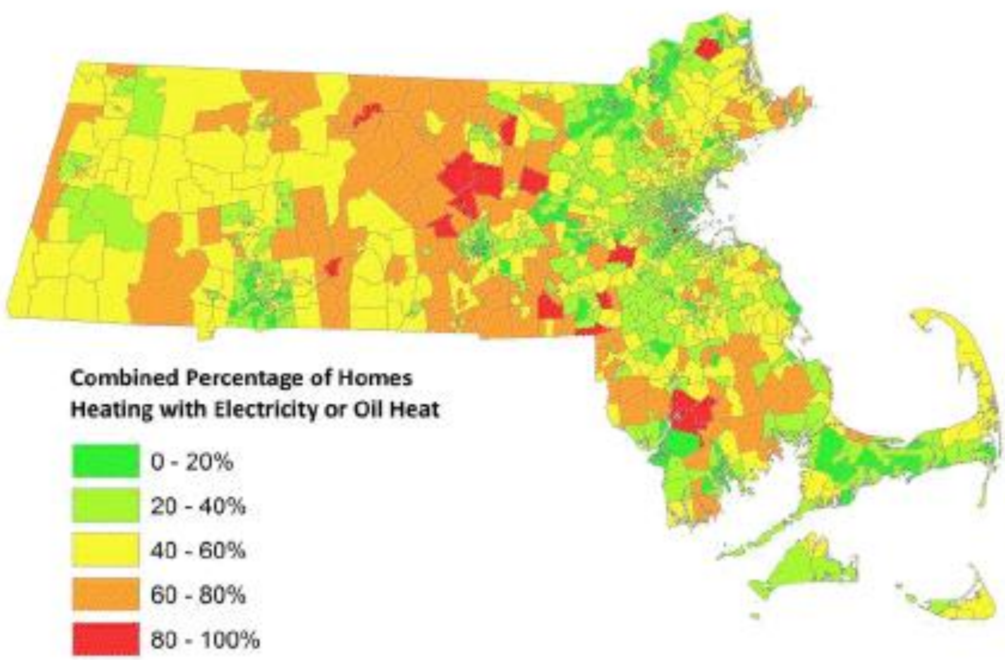

Figure 5: Percentage of Homes Heating with Electricity or Oil Heat

Wood pellet boilers; as there is not an excess supply of them and few companies to manufacture new ones; also tend to cost more than boilers which run off of more common types of fuel such as natural gas and oil. A typical wood pellet boiler for a residential setting costs between $18,000 and $20,000, while a high efficiency fossil fuel powered system typically costs $8,000 to $10,000 (DOER, 9). This high upfront cost is common of many renewable heating systems, including solar and geothermal. These types of heating systems rely on a low cost of operation or a low fuel cost to make up for the difference in upfront cost.

Because of the large price increase involved with purchasing a wood pellet boiler instead of another boiler type and the availability of natural gas as a cleaner, cheaper, more convenient fuel source in many areas, wood pellet boiler conversions are reasonable only in buildings where natural gas is not currently an option for fuel. In Massachusetts, fuel oil consumption produces only 39 trillion BTU of heating energy in commercial buildings larger than 10,000 square feet, while natural gas consumption is responsible for 72 trillion BTU of heating energy (*Buildings Energy Data Book*).

Using these figures, a yearly production of 2.3 million tons of pellets would be enough to sustain a heating infrastructure where all current oil based heating systems were replaced with wood pellet fueled systems, much less than the original requirement of 9.55 million tons for all heating to be converted to wood pellet fueled systems. This situation would require only about 5.6 million tons of harvested biomass to create the required amount of pellets.

Converting only those commercial building which currently rely on oil for heating fuel to wood pellet fueled systems would require the consumption of only slightly more wood than is available for pellet manufacturing making this the most plausible situation for wood pellet fueled heating conversions that does not involve the use of wood harvested for non-fuel related purposes.

6. Current Sites

6.1 Anna Maria College

Figure 6: 5.63 MM BTU/hr Wood Pellet Fueled Boiler Installed at Anna Maria College in Paxton, MA

6.1.1 Expectations for First Year

Anna Maria College houses the largest wood pellet fueled boiler in Massachusetts, producing around 5.63 MM BTU/hr, in order to supply about 90% of the 341,000 sq. ft. campus with heat. The new boiler, as would be the case for modifying many other existing systems, was simply retrofitted to the old network of steam pipes. In its first year of operation, the new wood pellet system was expected to consume around 30 tons of pellets per week, which were stored in a silo outside of the boiler facilities that would need to be refilled weekly (a process which was expected to take around 30-40 minutes), for an expected savings of around 50% over the price of #2 heating oil. The 30 tons of pellets, after being consumed in the boiler, is reduced to around 55 gallons of ash, which is to be used as fertilizer.

Because wood pellet furnaces must operate at around 30% of their total capacity in order to cleanly and completely burn their fuel, a small auxiliary oil burning furnace was kept in the facilities throughout the renovation in order to provide heat to the campus when there is low demand for heat, or when the demand may exceed that of the new boiler. It was also expected that maintenance of the furnace would require around 30 minutes per week, most of which was spent simply cleaning the interior of the burner to prevent ash build-up.

6.1.2 Results for First Year

After the first heating season, from the second week of October until the first week of April, a total of 720 tons of pellets was consumed, averaging about 28 tons of pellets per week. During previous heating seasons, during which the campus was heated with #2 heating oil, fuel costs were generally around $230,000. The cost of fuel for this heating season totaled $137,000, a savings of over 40%.

Maintenance proved to be something of an issue during this first season however. Initially, maintenance was scheduled to occur monthly, but by the end of the season was occuring on a weekly basis, though the maintenance was for simple cleaning and general upkeep, and not related to any sort of system malfunction. Along with the general maintenance, the boiler also requires several parts to be replaced annually to ensure continued, proper function. These replacement parts will cost around $20,000 for each year that the boiler remains in operation, which still represents a yearly savings of about 33% over operation of an oil fueled system.

Also, as was the case with the previous boiler, a certain standard had to be met regarding the emissions from the new pellet fueled system. While the system passed emissions regulations, it was very close to the upper limit allowed for particulate matter in emissions, at around 1 ppm of solid particulate matter. If the emissions had not met these regulations, the installation of an exhaust filtration system would have been required. The emissions filtration would not subtract from year to year savings in any meaningful way, but would have required a large up front cost to purchase and install the system.

Assuming this first season is representative of an average heating season, the upfront cost of the system and installation will be recuperated in about 10 years. However, as wood pellets fueled heating systems become more widespread and more pellet manufacturers begin production of fuel, it is expected that the cost of fuel will drop and the investment would be recuperated quicker.

7. Conclusion

Wood pellets, 0.while serving as a low cost and sustainable heating fuel, are not ideal for all situations. Although the fuel itself is low cost, the upfront cost of the boiler presents a major obstacle to expansion of the market. In urbanized areas, such as Boston, Worcester, and Springfield, natural gas is available as a cheaper, cleaner burning alternative to wood pellets. However, natural gas fueled systems rely on regional pipeline systems to deliver fuel to the heating system, which are not installed unless there is a large demand for natural gas in this area. Because of this and other alternative fuel types, wood pellets only serve as a viable option for heating fuel in a relatively small market in Massachusetts. Worcester Polytechnic Institute, only 8.5 miles from the wood pellet heated Anna Maria College, would likely not benefit from installing its own wood pellet fueled heating system. Because there is a natural gas line available to WPI and it is in a more densely populated area, meaning there are tighter regulations on the emissions due to the greater total amount of emissions released by other buildings in the area, installing this type of heating system would likely increase costs compared to the current system; not only from increased fuel costs, but also the increase in price associated with installing a wood pellet boiler, and in this area, possibly installing an emissions filtration system. However, because of the developing wood pellet market in New England, it is possible that wood pellets will soon rival natural gas in price and will be able to serve as a viable fuel for a larger number of situations. If this does occur, it would be in the best interest of buildings with higher heating needs to adopt the technology, as they will see the greatest amount of savings.

With natural gas serving as the main heating fuel for Massachusetts, wood pellet usage is currently limited to commercial buildings in less populated areas of the state, which require only about 50% of the total heating energy provided by natural gas fueled facilities. Where it is a viable option however, wood pellets cost about half as much per BTU as most fuel oils, but also require more maintenance and have a higher maintenance cost compared to oil fueled systems. Supposing all commercial buildings currently heated by fuel oil were to convert to wood pellet fueled systems, enough wood pellets could be produced from waste wood alone to supply all of the new systems. If waste wood were collected from all New England states, New Brunswick, and Quebec; assuming per acre waste wood production is close to that of Massachusetts; there would be enough waste biomass to supply a market 50 times the size of the viable Massachusetts market. With this amount of renewable fuel available at low cost, and a manufacturing process that uses only waste from other industries, wood pellet fueled heating systems offer an attractive alternative to many fossil fuel based systems.

Works Cited

"Air Emissions Fact Sheet." Ministry of Environment of British Columbia, n.d. Web. 30 Apr. 2013. <http://www.env.gov.bc.ca/epd/industrial/factsheets/pdf/wood-pellet.pdf>.

Alerich, C. L. 2000. "Forest statistics for Massachusetts: 1985 and 1998." USDA Forest Service Resource Bulletin NE-148

Berlick, Mary M., Kittredge, David B., and Foster, David R. "The Illusion of Preservation." *Harvard Forest Paper No. 26.* Web. 10 February 2013. <http://masswoods.net/sites/masswoods.net/files/pdf-doc-ppt/IllusionofPreservation_0.pdf>

"Biomass Basics." *Partnership For Policy Integrity*. N.p., n.d. Web. 30 Apr. 2013.<http://www.pfpi.net/biomass-basics-2>.

Biomass Sustainability and Carbon Policy Study. Rep. Biomass Sustainability and Carbon Policy Study, June 2010. Web. 16 May 2013. <http://www.manomet.org/sites/manomet.org/files/ Manomet_Biomass_Report_Full_LoRez.pdf>.

"Boiler Emission Guide." Cleaver-Brooks Inc, n.d. Web. 30 Apr. 2013. <http://www.cleaverbrooks.com/uploadedFiles/Internet_Content/Reference_Center/Insights/ Boiler%20Emissions%20Guide.pdf>.

Brooks, Robert T., Dickson, David R., Burkman, William G., Millers, Imants, Miller-Weeks, Margaret, Cooter, Ellen, and Smith, Luther. "Forest Health Monitoring in New England: 1990 Annual Report." United States Department of Agriculture. Web. 16 May 2013. <http://www.fs.fed.us/ne/newtown_square/publications/resource_bulletins/pdfs/scanned/OCne_rb125.pdf>

"Carbon Emissions." *Partnership For Policy Integrity*. N.p., n.d. Web. 30 Apr. 2013. <http://www.pfpi.net/carbon-emissions>.

"Controlling Emissions in a Growing Wood Pellet Marketplace." *Biomass Magazine*. N.p., n.d. Web. 30 Apr. 2013. <http://biomassmagazine.com/articles/2469/ controlling-emissions-in-a-growing-wood-pellet-marketplace>.

Cunningham, Kyle, and David Patterson. *Forest Landowner's Guide to Field Grading Hardwood Trees*. Tech. University of Arkansas Division of Agriculture. Print.

de la Crétaz, Avril L. 1, Fletcher, Lena S. 1, Gregory, Paul E. 2, VanDoren, William R. 1 and Barten, Paul K. 1. "An Assessment of the Forest Resources of Massachusetts." *Massachusetts Department of Conservation and Recreation* (1) and *University of Massachusetts Amherst Department of Natural Resources Conservation* (2). Web. 20 March 2013. <http://www.mass.gov/dcr/stewardship/forestry/docs/Assessment_of_Forest_Resources.pdf>

" DRY IMPINGER METHOD FOR DETERMINING CONDENSABLE PARTICULATE EMISSIONS FROM STATIONARY SOURCES." *CleanAir*. N.p., n.d. Web. 30 Apr. 2013. <http://www.cleanair.com/EPAMethods/Air-Test-Methods/m-202.html>.

"Emissions and Costs of Electricity from Coal, Natural Gas, Wood Pellets." *Journalists Resource RSS*. N.p., n.d. Web. 30 Apr. 2013. <http://journalistsresource.org/studies/environment/climate-change/substituting-biomass-coal>.

"FAQ." *Pellet System International*, 10 April 2013. <http://www.pelletsystems.com/index.html>

"Forestry in New Brunswick." *Riparian Habitat Restoration*. Web. 4 February 2013. <http://riparianhabitatrestoration.ca/Plans/fnb.htm>

Gauthier S, Grass H, Lory M, Krämer T, Thali M, and Bartsch C. Lethal. Carbon Monoxide Poisoning in Wood Pellet Storerooms -- Two Cases and a Review of Literature. Institute of Legal Medicine, University of Zurich. Web. 15 April 2013. <http://www.ncbi.nlm.nih.gov/pubmed/22879445>

Global Wood Pellet Production from 2010 to 2012, by Region. Web. 16 May 2013. <http://www.statista.com/statistics/243906/global-wood-pellet-production-outlook/>

"Guide to New Hampshire Timber Harvesting Laws." *University of New Hampshire Cooperative Extension*. Web. 5 February 2013 <http://extension.unh.edu/resources/files/resource000253_rep274.pdf>

"Hardwood vs. Softwood." *Cypress Pacific Marketing*. N.p., n.d. Web. 16 May 2013. <http://www.harrisenergyinc.com/pdf/hardwoodvssoftwood.pdf>

Harper, David, Jones, David, Taylor, Adam. "An Introduction to their Production and Use." *Wood Pellets*. Web. 16 May 2013. <http://msucares.com/pubs/publications/e0021.pdf>

Heating and Cooling in the Massachusetts Alternative Portfolio Standard. Rep. Executive Office of Energy and Environmental Affairs, Dec. 2012. Web. 16 May 2013.

"Heating, Cooling & Air." *Buyer's Guide to Pellet- and Wood-burning Stoves*. N.p., n.d. Web. 30 Apr. 2013. <http://www.consumerreports.org/cro/appliances/heating-cooling-and-air/wood-stoves/ buyers-guide-to-pellet-and-wood-burning-stoves-1-07/overview/0701_pellet-stove.htm>.

How It's Made: Wood Pellets. *Science Discovery*. Science. Web. 10 March 2013. <http://science.discovery.com/tv-shows/how-its-made/videos/how-its-made-wood-pellets.htm>

"Industrial/Commercial/Institutional (ICI) Boilers." *Combustion Portal*. N.p., n.d. Web. 30 Apr. 2013. <http://www.combustionportal.org/boilerregulations.cfm>.

Kuokkanen, Matti, Vilppo, Teemu, Kuokkanen, Toivo, Stoor, Tuomas, and Niinimaki, Jouko, Additives in Wood Pellet Production - A Pilot-Scale Study of Binding Agent Usage, *bioresources.com*, <http://www.ncsu.edu/bioresources/BioRes_06/BioRes_06_4_4331_Kuokkanen_VKSN_Chem_Tech_Binding_Agent_Wood_Pellet_1782.pdf>

“Maine Public Reserved, Nonreserved, and Submerged Lands 2011 Annual Report.” *Maine Department of Conservation*. Web. 5 February 2013. <http://www.state.me.us/doc/parks/pdf/2011landsannualreport.pdf>

Murray, Gordon. “Canadian Wood Pellet Export Outlook.” *Wood Pellet Association of Canada*. Web. 16 May 2013. <http://www.pellet.org/images/17_Murray_-_WPAC.pdf>

"Particulate Matter." *EPA*. Environmental Protection Agency, n.d. Web. 30 Apr. 2013. <http://www.epa.gov/airquality/particlepollution/index.html>.

"Particulate Matter." *Particulate Matter*. Hamilton County Environmental Services, n.d. Web. 30 Apr. 2013. <http://www.hcdoes.org/airquality/monitoring/pm.htm>.

Simet, Anna. “North American Wood Pellet Exports up 70 Percent 3Q 2012.” *Biomass Magazine*. Web. 16 May 2013. <http://www.biomassmagazine.com/articles/8570/north-american- wood-pellet-exports-up-70-percent-3q-2012>

Spelter, Henry, and Toth, Daniel. “North America’s Wood Pellet Sector.” USDA. Web. 16 May 2013. <http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf>

“Statistical Abstract of the United States 2012, Section 1: Population.” U.S. Census 2010. Web. 10 April 2013. <http://www.census.gov/prod/2011pubs/12statab/pop.pdf>

“Rigorous and Adaptive Forest Management - Main highlights.” *Quebec Natural Resources*. Web. 4 February 2013. <http://www.mrn.gouv.qc.ca/english/forest/understanding/understanding-forest.jsp>

"The Annals of Occupational Hygiene." *Lethal Carbon Monoxide Poisoning in Wood Pellet Storerooms-Two Cases and a Review of the Literature*. N.p., n.d. Web. 30 Apr. 2013. <http://annhyg.oxfordjournals.org/content/56/7/755.long>.

"The Energy Index for Commercial Buildings." *Buildings Energy Data Book*. Web. 16 May 2013.

"US Biomass: Where Do All the Wood Pellets Go?" *RE News RSS*. N.p., n.d. Web. 30 Apr. 2013. <http://www.renewableenergyworld.com/rea/news/article/2012/06/where-do-all-the-wood-pellets-go>

"U.S. National Ambient Air Quality Standards." *U.S. National Ambient Air Quality Standards*. N.p., n.d. Web. 30 Apr. 2013. <http://www.eoearth.org/article/U.S._National_Ambient_Air_Quality_Standards>.

United States. Government Printing Office. *Code of Federal Regulations*. GPO, 2008. Web. 15 Apr. 2013. <http://www.gpo.gov/fdsys/pkg/CFR-2012-title40-vol7/pdf/CFR-2012-title40-vol7- sec60-43.pdf>.

Walker, Thomas, Cardellichio, Peter, Colnes, Andrea, Gunn, John, Kittler, Brian, Perschel, Bob, Recchia, Christopher, and Saah, David. "Biomass Sustainability and Carbon Policy Study." *Manomet Center for Conservation Sciences*. Web. 16 May 2013. <http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf>

"What Is a Baghouse?" *EHow*. Demand Media, 14 Sept. 2009. Web. 30 Apr. 2013. <http://www.ehow.com/about_5417338_baghouse.html>.

Woodford, Chris. (2008) Electrostatic smoke precipitators. Retrieved from http://www.explainthatstuff.com/electrostaticsmokeprecipitators.html. [Accessed 4/19/13]

"Wood Gasification." Renewable Energy Training Center, Morrisville State College. Web. 16 May 2013. <http://www.morrisville.edu/documents/retc/oswegatchie_09_modules/woodgas_biofuel_module/ Wood%20Gasification%20(final).pdf>

"Wood Pellets vs. Oil Pollution: Emission Study Faults Wood, but Findings Debated."*Fosters.com - Dover NH, Rochester NH, Portsmouth NH, Laconia NH, Sanford ME*. N.p., n.d. Web. 30 Apr. 2013. <http://www.fosters.com/apps/pbcs.dll/article?AID=/20080907/GJNEWS_01/709079926/-1/FOSNEWS>.